Assessment of Cellular Telephone and Other Radio Frequency Exposure for Epidemiologic Research

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Epidemiologists are now embarking on the evaluation of the hypothesis that exposure to radio frequency energy from low-power wireless communication devices, such as portable cellular telephones, causes brain cancer and other adverse health outcomes. Even in the laboratory, exposures from radio frequency sources are difficult to quantify; their measurement in large populations for epidemiologic study is challenging. In this paper, we outline the nature and magnitude of these exposures and discuss the prospects for obtaining useful measures of exposure for epidemiologic research. (Epidemiology 1996;7: 291–298)

Keywords: cellular telephones, radio frequency energy, cancer, electromagnetic radiation, study design.

The rapid growth of cellular telephone technology has brought with it concerns about radio frequency (RF) exposures. Cellular telephones are a primary source of RF exposure to individuals in the environment. In this paper, we review cellular technology, describe the nature and magnitude of RF exposures from this technology as well as other sources of RF exposure, and consider factors that affect epidemiologic research in this area.

Cellular Technology

Cellular technology provides a two-way radio communications system similar to, but of lower power than, that utilized by police, fire, or emergency services. Cellular technology divides a given geographical region into zones called "cells," each of which is equipped with a "base station"—an RF transceiver and associated computer equipment. When a call is placed from a cellular telephone within a cellular network, a signal is sent from the cellular telephone antenna to the base station antenna, and the base station responds by assigning an available RF channel. Communication is accomplished through the simultaneous transmission and reception of modulated radio signals, which carry the voice information between the cellular telephone and the base station. The base station routes the voice signals through a switching center, where the call can be transferred to another cellular telephone or to the local (landline) telephone system.

The amount of RF exposure is largely determined by the power level of the signal, which in turn depends on a number of factors. Cell coverage varies with the amount of cellular telephone traffic. Whereas a cell in a rural area may extend its coverage over a radius of many miles, cells in urban areas may cover only a fraction of a mile. The farther the telephone is from the base station antenna, the higher the power level needed to maintain the connection. In larger cells, therefore, telephone power levels will on the average be higher than those in smaller cells. Each cell also performs its service with a varying number of channels. Optimal use of these channels depends on limiting interference from adjacent channels. Cellular telephones are therefore designed to step down automatically to the lowest power level that maintains communication with the base station. The system used to control power output adjustment is defined by each cellular company. Some companies design their systems so that power output for all cellular telephones in their area is restricted to 0.6 watt (W) or less. This power limitation reduces interference but may require more cell sites to cover an area. Anything that inhibits the signal from the cellular telephone to the cell site (for example, buildings, mountains, foliage) will also reduce the signal at the cell site and automatically result in increased power output of the telephone. Handheld

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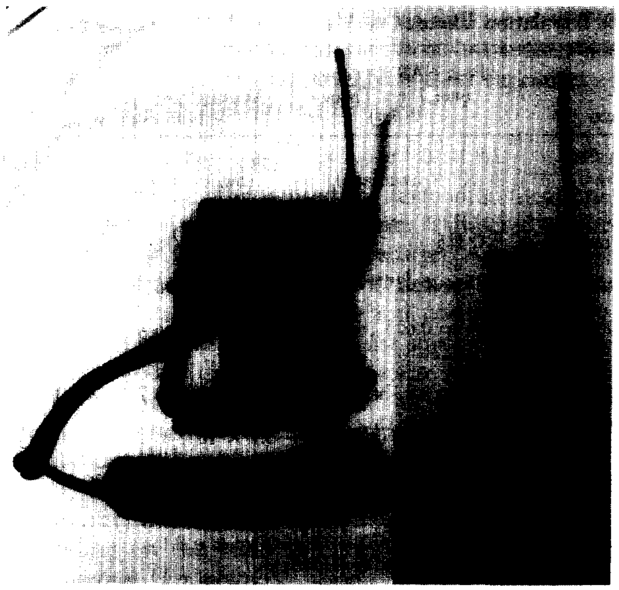

FIGURE 1. Transportable (*left*) and portable (*right*) cellular phones.

(portable) telephones are automatically set to operate at 0.6 W or less, regardless of the cellular telephone company, the cell coverage, the local geography, or the time of day.

There are four types of wireless telephones—mobile, transportable, portable, and cordless. The first three types are "cellular"; cordless telephones are not. Mobile telephones ("car phones") usually have their antennas mounted on the vehicle roof, trunk, fender, or window. Because of the physical separation of the antenna from the user and the shielding of the metal surface of the vehicle, users of car telephones receive little exposure to RF energy. Transportable telephones, or "bag phones," have the antenna and associated equipment in a small carrying case (Figure 1). As the antennas of transportable telephones may be positioned close to the body of the user, these types of telephones present the possibility of greater exposure than car telephones. Portable cellular telephones have antennas incorporated into the telephone unit (Figure 1). Exposure to the head is greater than with either car telephones or bag telephones. Cordless telephones have a base unit that is wired to the landline telephone service; these telephones operate at about 1/600 the power of cellular telephones and at a much lower frequency (49 MHz).

The Electromagnetic Spectrum

The "frequency" of an electromagnetic (EM) wave is determined by the number of wave peaks passing a given location in 1 second. Figure 2 illustrates the location of various frequency bands of EM waves. Use of the EM spectrum is regulated by the Federal Communications Commission (FCC). Each application, such as electric power, television broadcast, or cellular communications, is assigned its own range of frequencies. The allocation for cellular telephone service is in the RF band, between 800 and 900 MHz. RF is distinct from extremely-low-frequency (ELF) energy, the energy associated with electrical power transmission.

The EM spectrum can be divided into two categories according to how the wave interacts with biological tissue: ionizing and non-ionizing (Figure 2). X-rays and other ionizing radiation have extremely high frequencies (greater than 10^{15} Hz) and can affect the chemical composition of materials and thus cause direct damage to tissue. Non-ionizing radiation can cause motion of electrical charges and conversion of energy into heat in exposed materials. By this means, a microwave oven heats food. EM energy emitted by cellular telephones, however, is not of sufficient level to cause detectable heating of biological tissue.[1] It is still an open question, however, whether RF exposures too weak to increase temperature measurably could have biological effects.

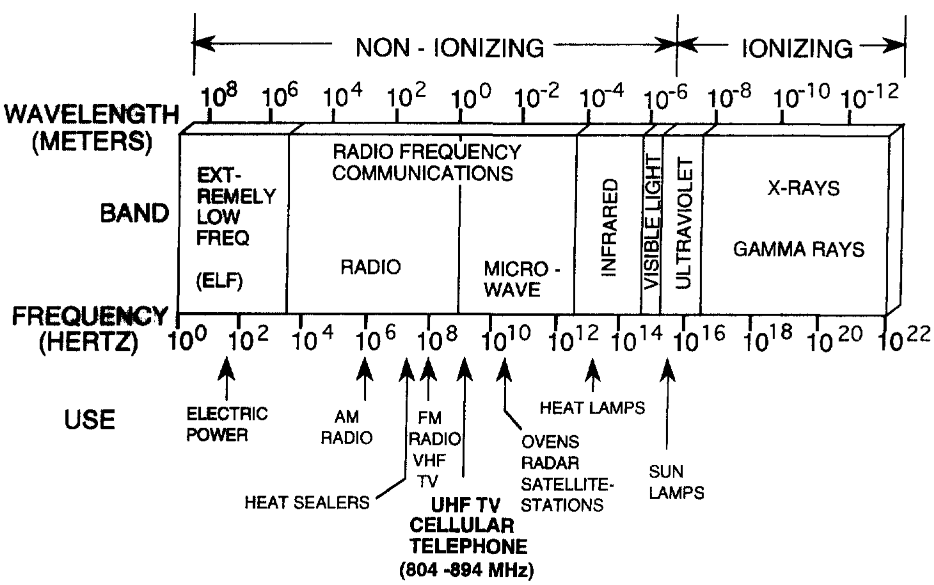

FIGURE 2. Electromagnetic wave spectrum.

TABLE 1. **Maximum Specific Absorption Rate (SAR) in U.S. Population Exposed to Various Radio Frequency Sources**

Authors	Population	Size	Radio Source	Peak SAR (Average over 1 gm Tissue W/kg)	Average SAR (Average over Whole Body W/kg)
Tell, Mantiply (1980)[2] Durney *et al.* (1986)[3,*]	15 largest U.S. cities	44,125,176	Background (mainly FM broadcast stations)	3.8×10^{-6} to 1.6×10^{-5}† (medians)	1.9×10^{-7} to 8.4×10^{-7} (medians)
Balzano *et al.* (1995)[19]	CB users	14,000,000	Handheld 27 MHz radios	<0.3‡§	$<2.14 \times 10^{-4}$
Balzano *et al.* (1995)[19]	Amateur radio operators	660,000	Handheld VHF radios	0.25 to 0.625§	1.8×10^{-3} to 4.5×10^{-3}
Balzano *et al.* (1995)[19]	Police and emergency services	Uncertain	Handheld VHF radios	0.25 to 0.625 (brain)§	1.8×10^{-3} to 4.5×10^{-3}
Gandhi (1995)[4]	Cellular phone users	25,000,000	Handheld cellular phones	0.09 to 1.9 (hand)‖	8.1×10^{-4} to 2.35×10^{-3}‖
Gandhi (1995)[4]	Cellular phone users	25,000,000	Handheld cellular phones	0.16 to 0.69 (head)‖	8.1×10^{-4} to 2.35×10^{-3}‖
Gandhi (1995)[4]	Cellular phone users	25,000,000	Handheld cellular phones	0.06 to 0.41 (brain)‖	8.1×10^{-4} to 2.35×10^{-3}‖

* Tell and Mantiply[2] provided exposure information in $\mu W/cm^2$; conversions to W/kg were done using information provided in Durney *et al.*[3]

† Peak SAR was assumed to be 20 times whole body average, which is the basis of peak SAR allowed by U.S. exposure standards.

‡ Maximum sensitivity of measurement instrument.

§ Measured in laboratory model.

‖ Calculated.

Population Exposure to RF Sources

Use of handheld cellular telephones is now the primary source of RF exposure to the general population, but not the only source. The general population is subject to ambient RF exposure from broadcast signals and cellular base stations. Devices other than cellular telephones also emit this type of RF energy. Users of numerous portable and mobile communication devices are exposed. A limited number of people are exposed through hobbies or similar activities [ham and citizens band (CB) operators]. The specific absorption rate (SAR) is a dosimetric parameter that is commonly used in RF studies to assess exposure; it is discussed below in greater detail. Table 1 summarizes the peak and average SARs for several different populations so that exposure in cellular telephone users can be compared with exposure levels in other groups (Balzano Q, Motorola Corp., Plantation, FL, private correspondence, 1995; Refs 2–5). Each exposure source is discussed below, in order of exposure potential, starting with the greatest.

Portable Cellular Telephones

RF exposure from wireless technology depends on the duration of use, the number and length of individual calls, and the location of the calls (for example, local topography, cell site density, and use inside/outside buildings). Exposure may also vary depending on the type of modulation. Most current cellular systems are "analog" systems employing signals (804–894 MHz) of constant amplitude. Cellular companies are beginning to install "digital" systems, which use complex modulation schemes to increase carrying capacity. These two systems may produce exposures that potentially have different biological interaction.[6–9] Next-generation wireless technology will employ somewhat higher frequencies (1,800–2,200 MHz), exclusively digital modulation, and lower average power levels.

Exposure also varies with individual habits of use. Exposure is localized to the side of the head on which the telephone is used (laterality), so individuals who hold the telephone to the left or right ear exclusively will have different tissue exposures on each side. Wire-rimmed glasses, metal implants, and jewelry also may alter the location and degree of energy absorption, although the effect of these factors has not yet been thoroughly investigated.

Noncellular Mobile Communication Devices

Antennas for mobile transceivers (for example, two-way car radios, such as those installed in police cruisers and taxis) are usually mounted on the roof, the front or rear deck, the fender, or, at low frequencies, the rear bumper of vehicles; their transmitters operate at power levels up to 100 W. Exposure of the occupants of the vehicle or of bystanders depends on radiated power, frequency, type of installation, and accessibility of the antenna. Information provided to the FCC by one manufacturer indicated that the exposure of a bystander from a 100-W mobile antenna may exceed the 1982 American National Standards Institute (ANSI)-recommended limits at distances up to 30–50 cm from the antenna.[10,11] The duty factors (proportion of time spent transmitting), however, are low, and actual time-averaged exposure at these distances is probably within current safety limits.

Radio and Television Broadcast

The U.S. Environmental Protection Agency collected broadcast signal field intensity data for 3 years to estimate population exposure to this form of non-ionizing radiation. Measurement data were collected at 486 locations in 15 large cities. The 1980 data showed that the main sources of ambient RF exposure in the United States are VHF and UHF broadcasts. At the time of those measurements, cellular base stations were not in existence. Population exposures to broadcast sources are one or more orders of magnitude less than exposures of users of portable cellular telephones.

Cellular Base Stations

As with other antennas used for telecommunications, the energy from a base station antenna is directed toward the horizon, with some downward scatter. As one moves away from the antenna, the power density decreases as the inverse square of the distance and, consequently, the exposure at ground level near a base station is relatively low compared with the exposure close to the antenna itself. Ground level exposure is well below exposure limits recommended for the general and occupational populations.[12–15]

The power density levels inside buildings near a base station antenna can be 10–100 times lower than outside, depending on the building construction.[10] For typical construction (for example, wood or cement block), the attenuation is a factor of about 10. In rooms directly below roof-mounted installations, the power density levels are considerably lower than roof locations, depending on the construction. The power density behind sector (directional) antennas is hundreds to thousands of times lower than in front, and, therefore, levels are well below exposure limits in rooms directly behind walls where sector antennas are mounted on the sides of buildings.

Automobile Cellular Telephones

The output power of an automobile-based cellular transceiver, which transmits in the 824- to 850-MHz band, is controlled by the base station and generally does not exceed 3 W. In a vehicle equipped with a cellular transceiver, the exposure levels to driver and passengers are strongly affected by the antenna type and location.[16] When the antenna is at the center of the trunk lid, the exposure above the rear seat, at head level, depends mainly on the distance from the radiating structure. If the car has a plastic body, any shielding effect of the metal surface is lost. Even at a distance of 30 cm from the antenna, however, the exposure to the user is substantially lower than the 1986 guidelines for exposure to the general public.[14 p.275]

Dosimetry

Because RF radiation interacts with biological systems in complex ways, the quantification and distribution of energy absorption is difficult to assess. Coupling, or transferring of EM energy to tissues, varies with many factors. The fundamental parameters of tissue interactions are the electric and magnetic fields induced in the tissues and the currents and energy associated with these fields, which depend on the tissue absorption properties and the size and shape of the affected site.

Definition of Power Density and Specific Absorption Rate

The external field intensity may be expressed using a variety of parameters. Exposure data may be expressed in terms of power density (mW per cm^2), external electric field strength (V per m), or magnetic field strength (A per m). None of these measures provides insight about how the fields interact with biological tissue. Therefore, many investigators now rely on dose rate, which was formerly termed "absorbed power density."[17] This parameter has been designated the specific absorption rate by the National Council on Radiation Protection and Measurements (NCRP). The SAR is defined essentially as the time derivative of the energy absorbed by (dissipated in) an incremental mass contained in an incremental volume of a given density.[14] The absorption of energy results in a minuscule temperature increase for low SAR values. Although SAR can be obtained by measuring the temperature increment, this fact does not imply that biological interaction mechanisms are necessarily thermal. Even when a mechanism is determined to be "athermal," however, SAR is an appropriate dosimetric parameter, as it specifies the induced electric fields and current densities, including peak values for amplitude-modulated fields.

Factors That Determine Energy Absorption in Tissues

For an individual user, SAR will be determined by EM field frequency and intensity, dielectric properties of the tissues (largely a function of water content), tissue geometry and size, tissue orientation and field polarization, antenna configuration, exposure environment, and signal modulation. For example, among individuals, anatomic variation such as fat and bone thickness and head size will influence energy coupling. Whether the antenna is extended or left within the handset also greatly affects EM fields in tissues and thereby energy absorption. If a signal is amplitude or pulse modulated, the SAR also varies over time. Frequently, a time-averaged SAR is specified for amplitude- or pulse-modulated signals.

Tissue Exposure

RF energy deposition in users of cellular telephones is caused essentially by magnetic fields that induce eddy currents in the exposed tissues.[18,19] Human equivalent models are used experimentally to measure specific absorption and SAR, but the models, the methods, and the procedures are far from being standardized in RF dosimetry.

Using a liquid tissue equivalent model and electric field probes, the SAR values near the surface of the head (0.4 cm depth) were obtained for two types of portable telephones. There are some common features in the iso-SAR contours of Figures 3 and 4. First, metal parts of the radio case containing the electronics carry RF currents that are placed close to the face (the ipsilateral cheek) of the users. These currents, although much weaker than the RF currents on the antenna, are so near the face that, in normal use, the face is by far the most intensely exposed part of the body. According to one set of measurements (Figure 4), the highest SAR (1.1 W per

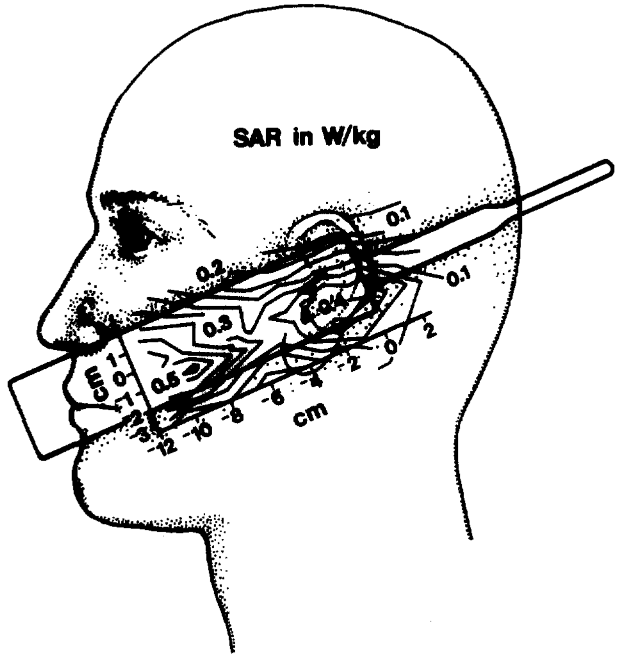

FIGURE 3. Iso-SAR map. Classic "banana" portable telephone. Adapted from Balzano *et al.*[19]

kg) was seen on the cheek at and adjacent to the earlobe. Gandhi and colleagues[4] have calculated theoretical SAR patterns in the heads of cellular telephone users exposed to a variety of cellular telephone instruments. Their results are shown in Table 1.

The presumed SAR values displayed in Figures 3 and 4 are peak values that can be expected at the head surface. The exposure of brain tissue is substantially

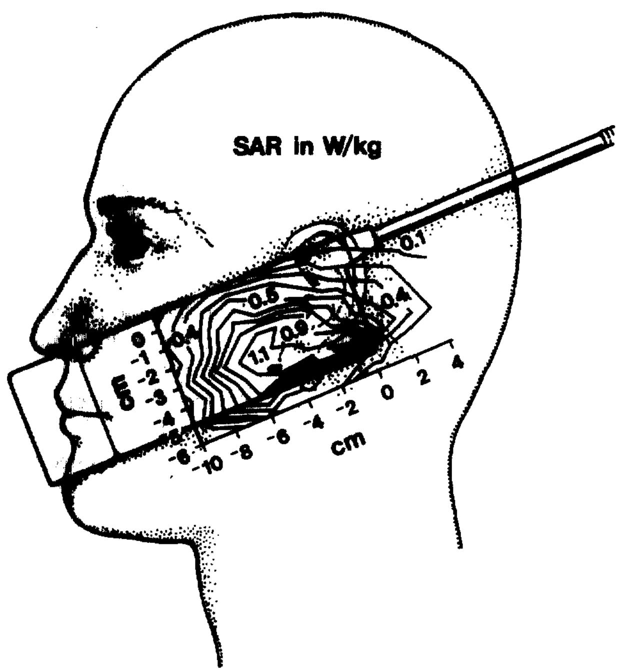

FIGURE 4. Iso-SAR map. "Flip" portable telephone. Adapted from Balzano *et al.*[19]

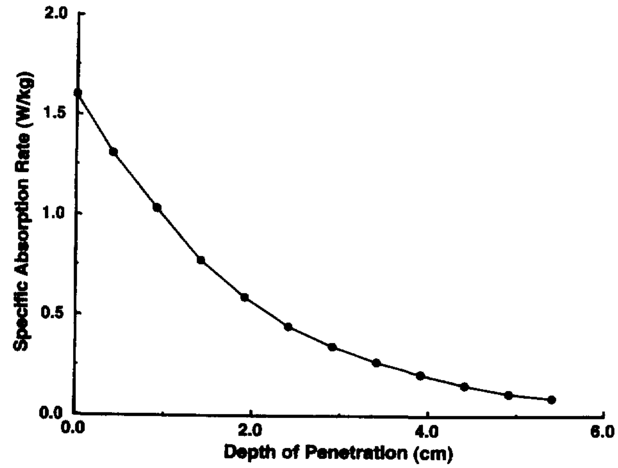

FIGURE 5. SAR attenuation in simulated brain tissue at 835 MHz.

lower (by a factor of as much as 2) than the peak value of the SAR in the face. SAR averages expected through the outer 1 cm of brain tissue will be 20–30% lower than the surface measurements in Figures 3 and 4, because the RF energy is rapidly dissipated as it is propagated through the brain (Figure 5). Within a distance of 5 cm, the energy is attenuated by over 90%, so the SAR at the hypothalamic tract and the hypophysis is of the order of 0.1 W per kg. The exposure on the contralateral side is lower by more than one order of magnitude.

In view of this exposure pattern, SARs are relatively high only for glial and meningeal tissue at the outermost surface of the lower anterior portion of the parietal lobe, and only on the side of the head where the telephone is placed. Any active marrow in the flat bones of the cranium directly over this region would also be exposed. SARs would also be relatively high at the surface of the vestibular portion of the acoustic nerve, where acoustic neuromas (tumors) arise. SARs may be similarly high at the parotid gland, which is located in the cheek directly below the ear, starting at a depth of about 1 cm. SARs for the parotid gland, acoustic nerve, and cranial marrow have not been measured, however. SARs are substantially lower at other head and neck locations such as the cerebellum, midbrain, eyes, and thyroid gland.

Epidemiologic Study of Radio Frequency Exposure

The principle that the work place is the sentinel for the community may be extended here to include hobbies such as operating a ham radio as well as use of cellular telephones on the job. Two groups of workers experience occupational RF exposure: those who manufacture and/or repair RF-emitting appliances, and those who use the appliances. The manufacturing/repair group includes engineers and technical staff involved in radio or radiotelephone research and design, factory workers involved in product testing, and technicians doing repair or installation. U.S. industry has been involved in the design and manufacture of radiotelephones for over 50 years,

TABLE 2. Leukemia: Selected Results of Occupational or Recreational Exposure to Electromagnetic Energy

Authors	Study Type	Disease	Occupational Group	RR	95% CI
Calle, Savitz[20]	Cohort	Leukemia	Radio/telegraph operators	2.4	*0.9–5.1
			Radio/TV repairmen	0.9	*0.2–2.5
Coleman *et al*[21]	Cohort	Leukemia	Radio/radar mechanics	0.2	0.0–1.1
			Telegraph/radio operators	2.5	1.0–5.1
Garland *et al*[22]	Cohort	Leukemia	Electronics technicians	1.1	0.4–2.6
Hill[23]	Cohort	Leukemia	MIT radar lab workers	0.6	0.1–2.3
Lilienfeld *et al*[24]	Cohort	Leukemia	Moscow embassy staff	2.5	0.3–9.0
McDowall[25]	Cohort	Leukemia	Telegraph/radio operators	2.5	*1.0–5.2
			Radio/radar mechanics	0.6	*0.2–1.8
Milham[26]	Cohort	Lymphatic, hematopoietic	Radio/telegraph operators	1.4	*0.8–2.2
			Radio/TV repairmen	1.3	*0.7–2.2
			Electronic technicians	1.4	*0.9–2.2
Milham[27]	Cohort	Leukemia	Ham radio operators	1.2	0.9–1.7
Milham[28]	Cohort	Lymphatic, hematopoietic, other lymphatic malignancy	Ham radio operators	1.2 1.6	*1.0–1.5 *1.2–2.2
Pearce *et al*[29]	Case-control	Leukemia	Radio/TV repairmen	4.8	1.6–14.2
Pearce *et al*[30]	Case-control	Leukemia	Radio/TV repairmen	7.9	2.2–28.1
Robinette *et al*[31]	Cohort	Lymphatic, hematopoietic	Military radar exposed	1.2	*0.8–1.7
Robinson *et al*[32]	Cohort	Leukemia	Telegraph/telephone operators	1.9	0.6–4.6
Sahl *et al*[33]	Cohort	Leukemia	Electric utility workers	1.1	0.5–2.3
Savitz, Loomis[34]	Cohort	Leukemia	Electric utility workers	0.8	0.6–0.9
Szmigielski[35]	Cohort	Lymphatic, hematopoietic	Military personnel	6.3	3.1–14.3
Thériault *et al*[36]	Case-control	Leukemia	Electric utility workers	1.1	0.7–2.0
Wiklund *et al*[37]	Cohort	Leukemia	Telephone operators	1.0	*0.6–1.7
Wright *et al*[38]	Cohort	Leukemia	Electronic technicians	1.0	*0.3–2.3
			Radio/TV repairmen	1.2	*0.1–6.1

* Confidence intervals calculated from reported data.

with major efforts during World War II and thereafter. There are almost no data available, however, concerning historic RF exposure of either manufacturing or repair personnel. Military personnel are a second group with RF exposure, including many exposed to the pulsed signals used for radar.

There are more than 14,000,000 licenses submitted to the FCC for operation of CB radios. Transmitters operated by CB users include handheld transceivers operating at powers up to 5 W, or 8.33 times that of handheld cellular phones. Nevertheless, the energy absorption by the CB user is much less than that for the cellular phone user, owing to poorer coupling of 27-MHz energy to tissues. The peak SAR in the head of a CB user is less than 0.3 W per kg, and the estimated whole-body-average SAR for a 70-kg human is less than 2.14×10^{-4} W per kg.[5]

Many of the 660,000 amateur radio licensees in the United States utilize handheld radios operating in the VHF and UHF frequency bands. Measured SARs in human equivalent models vary; peak SARs (average over 1 gm of tissue) range from 0.25 to 0.650 W per kg, and whole-body-average SARs range from 1.8×10^{-3} to 4.5×10^{-3} W per kg.[19] The population of other users of handheld radios operating in the VHF and UHF bands includes police, emergency service workers, and workers involved with railways, forestry, mining, and construction. The measured SARs for these users are the same as obtained for amateur radio users.

The occupational user group is more difficult to define as cellular telephones become more ubiquitous and as various occupational groups discover their advantages. Thus, salespersons from many industries now use these telephones, along with health care professionals, construction managers, and other groups needing such communication. Compared with current users of cellular technology, ham radio operators and other hobby groups provide the opportunity to study people who have experienced potentially greater exposure intensities over longer periods.

Since there is no available cohort with measured RF exposure data, epidemiologists will have to use other, less quantitative exposure measures. From job titles, one can estimate probability of exposure, frequency of exposure (how often), and intensity of exposure. These three measures can be either used individually in analyses or combined into an index, along with job duration. Where quantitative measures are absent or impractical, there may be some utility in classifying people by type of exposure. Exposure types might include use of a communications device (for example, portable telephone), exposure to unshielded RF communications (for example, microwave antennae), or exposure to other RF emitters (for example, heat sealers, induction furnaces).

In Tables 2 and 3 are illustrated the variety of occupations and outcomes[20–42] (in particular, leukemia and brain cancer) that have been studied in relation to RF and other electromagnetic field exposures. The link between some of the occupations and actual exposure is tenuous, and results are inconsistent over the studies. Small study sizes may account for some of the inconsistencies. Almost all of the studies have the same weak-

TABLE 3. Brain Cancer: Selected Results of Occupational or Recreational Exposure to Electromagnetic Energy

Authors	Study Type	Disease	Occupational Group	RR	95% CI
Gallagher *et al*[39]	Cohort	Brain cancer	Radio/TV announcers, technicians	1.6	0.3–4.8
			Electronic repairmen, assemblers	0.8	0.1–2.8
Hill[23]	Cohort	Brain and CNS* cancer	MIT radar lab workers	1.1	0.2–3.1
Lilienfeld *et al*[24]	Cohort	Brain and CNS cancer	Moscow embassy	0.0	0.0–3.3
Milham[26]	Cohort	Brain cancer	Radio/telegraph operators	0.4	†0.0–1.9
Milham[28]	Cohort	Brain cancer	Ham radio operators	1.4	†0.9–2.0
Preston-Martin *et al*[40]	Case-control	Glioma	Various high-exposure groups	1.8	0.7–4.8
Sahl *et al*[33]	Cohort	Brain cancer	Electric utility workers	1.1	0.4–2.7
Savitz, Loomis[34]	Cohort	Brain and CNS cancer	Electric utility workers	1.0	0.8–1.1
Speers *et al*[41]	Case-control	Brain cancer	Utilities, communications, transportation	2.3	1.2–4.3
Szmigielski[35]	Cohort	Brain and CNS cancer	Military personnel	1.9	1.1–3.5
Thériault *et al*[36]	Case-control	Brain cancer	Electric utility workers	1.5	0.8–2.8
Thomas *et al*[42]	Case-control	Astrocytoma	Electronics manufacture and repair	4.6	1.9–12.2

* CNS = central nervous system.
† Confidence intervals calculated from reported data.

nesses of no validated RF exposure history, no data concerning other exposures (for example, chemicals), and use of broad occupational categories that may include many persons not exposed to RF energy. Although a few of these studies focused on RF exposure, the majority of these studies examined occupations with extra-low-frequency (ELF) and very-low-frequency (VLF) exposures.

The Potential for Extracting Exposure Indexes from Billing Records of Cellular Telephone Users

Because cellular telephone companies compile accurate billing logs of all telephone calls, the potential exists to use billing data to identify cellular telephone customers and to classify them according to the amount of their RF exposure. The billing systems of cellular telephone companies vary. Some contain the account holder's Social Security number and an equipment identifier (the electronic serial number, or ESN) directly in the billing system. Others either lack this information or keep it stored outside the billing system in a customer account file. All billing systems contain a customer name and address, the cellular telephone number, and some data on telephone use over a period of time. The use data are generally stored as minutes of use and total cost associated with that use for a specific interval. More detailed information on individual calls, including length and type (local *vs* roamer), may be available for limited periods of time. Customer status (for example, active, cancelled) and the date that service started (and ended, where appropriate) may also be maintained in the customer account file.

Even within companies, variation in record keeping between geographical areas can exist. For one large company, billing data for some locations are maintained centrally in a standard format and are available for up to 12 months of prior use. Data for other locations, however, are maintained locally in various cities served by the company. Long-term exposure is not readily accessible; the data are stored by monthly billing periods as opposed to longer periods of use (for example, yearly totals) and are not retained indefinitely.

Telephone type is the key determinant of RF exposure among cellular telephone users, because mobile telephones, in contrast to handheld portables, have negligible exposure. Although no indicator for telephone type is readily available from cellular telephone company records, it may be possible to determine telephone type from the manufacturers of the equipment, who keep records of the electronic serial numbers associated with each type of equipment.

Billing records contain the name and address of the account holder, but this individual is not necessarily the only—or even the primary—user of the telephone. Many corporate accounts have multiple users. For noncorporate accounts, use may be shared by family members or friends. A recent survey of almost 4,000 cellular telephone account holders found that about half of noncorporate respondents with one telephone use the telephone exclusively, and over two-thirds use the telephone at least 75% of the time.[43]

Direct Exposure Assessment

Direct exposure assessment from the user has some obvious advantages. Although the researcher must rely on the user's memory rather than on accurate records, the user can estimate personal use of the telephone as distinct from use by others. Self-reports of amount of use appear to be relatively reliable.[43] Furthermore, it is possible from interviews or questionnaires to obtain information on confounding factors, as well as on laterality, a key factor potentially related to the sites of tumors.

Questionnaires on cellular telephone use in epidemiologic studies should include, at a minimum, questions on the number and type of cellular telephones the respondent uses, whether or not the respondent is the sole or primary user of each, and some estimate of the amount and duration of use.

Conclusion

Epidemiologic studies of cellular telephone users will be important, as this expanding technology already produces the highest levels of RF energy exposure in the general population. The availability of billing records makes exposure to cellular telephone radio frequencies easier to measure than ambient exposures, such as those involving 60-Hz EM fields or trace chemicals. Nevertheless, it will be impossible for epidemiologic studies to obtain highly accurate individual estimates of exposure that take into account the actual signal strength of individual calls. Signal strength changes between calls and even during a single call. Billing data cannot distinguish which individual has used the telephone for each call. Although all epidemiologic measures are subject to inaccuracies, exposure to cellular telephone RF energy can still be estimated reasonably well with careful treatment of available data.

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Utility of Telephone Company Records for Epidemiologic Studies of Cellular Telephones

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We conducted a survey of over 5,000 telephone users who were customers of one large cellular telephone company covering four major geographical areas. Our primary goal was to assess the utility of ascertaining information on telephone use and type from telephone company records. We compared information from 3,949 respondents with corresponding data from company billing records. We found that 48% of the account holders were sole users, and 69% were the primary user, meaning that they accounted for at least 75% of the use. Respondent reports of amount of telephone use were highly correlated with data on the billing record ($r = 0.74$). Respondent reports of telephone type were similarly correlated with data from the manufacturer ($r = 0.92$). We also inquired about telephone holding patterns, since these have implications for exposure. Most users reported favoring one side of the head when using the telephone, but the side of the head used was not strongly associated with handedness. (Epidemiology 1996;7:299–302)

Keywords: cellular telephones, exposure assessment, reporting reliability, survey, data collection.

Few epidemiologic studies have examined the effects of radio frequency energy. Most of the focus related to non-ionizing radiation has been on exposures in the extra-low-frequency range.[1,2] Although cellular technology has been available for over 10 years, its growth has been exponential since 1990. By the end of 1994, there were 24 million cellular telephone users in the United States alone.[3] As the number of users increases, so does concern about safety.[4] We have begun epidemiologic surveillance of cellular telephone users by establishing a record-based cohort using account records from cellular telephone companies.[5] We undertook the present study primarily to assess the feasibility of using account information to assess the exposure of the account holder.

Cellular telephone company billing records have a number of potential limitations when used to construct an exposure index. First, billing records pertain to individual telephones, not to the users of those telephones. Although an account holder's name is associated with each telephone, the account holder may not be the primary user of the telephone. Thus, one objective was to ascertain the extent to which the amount of telephone use based on billing records corresponds to telephone use as reported by the account holder.

Second, company records do not include a direct indicator of the type of cellular telephone used in a given account. The concern about potential health effects from cellular telephone use relates to radio frequency exposure that decreases rapidly with distance from the transmitting antenna. Only handheld cellular telephones (as opposed to car telephones, for example) convey measurable radio frequency exposure to the user's head, since the antenna is located directly in the handset. Telephone company records do contain an electronic serial number (ESN) for each telephone that can be linked to telephone type from manufacturing records. Doing so, however, requires the cooperation of companies that manufacture cellular telephones. We wanted to determine whether the data on telephone type obtained from the manufacturer, after supplying them with ESNs from billing records, accurately represented information obtained directly from the user.

As noted, radio frequency exposure decreases rapidly with distance; during a cellular call with a portable telephone, the exposed area is limited to a portion of the side of the head where the telephone is held. If individuals consistently hold the telephone to one side of the head, any outcomes resulting from radio frequency exposure should also occur on that side of the head. We assessed the extent to which laterality of ear preference exists and whether handedness could be used as a surrogate in studies involving direct contact with users.

Methods

The subjects were a sample of all cellular telephone users from a major cellular company who were active users at the time of the survey and for whom revenue data and accurate identification information was available from the cellular company. A total of 5,550 cellular telephone users were selected from the four geographical areas

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TABLE 1. Distribution (Percentage) of Self-Reported Telephone Type by Geographical Area

Area	Number	Mobile in Car (N = 888)	Handheld (N = 1,133)	Bag Telephone (N = 1,143)	Multiple (N = 272)
Boston	854	29	24	35	12
Chicago	742	27	41	27	5
Dallas	915	16	50	25	9
Washington DC	925	33	17	44	6
All	3,436	26	33	33	8

covered by the company: Boston, 1,500; Chicago, 1,350; Dallas, 1,350; Washington DC, 1,350. We requested 1,350 users from each area; the Boston area supplied an additional 150 names, and we elected to include them. Each area represents a random, stratified sample that was selected by data processing personnel for each area. Customers were randomly selected from each of three revenue categories (low, $0–35.00; medium, $35.01–75.00; high, >$75.00), based on their average monthly bill over a 3-month period (1 month for Dallas). The 3 months selected were the same for three of the geographical areas, and the single month used by Dallas was in the same 3-month range.

The cellular telephone company mailed letters offering 30 minutes of free airtime for completing and returning an enclosed survey. A second mailing was sent to nonrespondents 10 weeks later. The questionnaire queried account holders on the kind of telephone they use (mobile installed in car, handheld portable, or transportable or bag phone), use (minutes per week) by account holder and others, laterality, handedness, gender, and date of birth. Use was assessed as follows: "About how many minutes per week do you yourself talk on your cellular telephone? If you are unsure, please make your best guess." A second question replaced "you yourself" with "other people." Laterality was assessed with two questions: "When you hold a telephone, against which ear do you hold it most often?" and "How often do you move the telephone from ear to ear during telephone calls?" Respondents were also asked whether they would describe themselves as primarily right- or left-handed.

We asked respondents for their cellular telephone number so that they could receive credit for the 30 minutes of free airtime. The cellular telephone company provided us with identifying information and billing data for the telephones in the sample for a 3-month period surrounding the period of the survey. The 3-month period was identical for all four geographical areas. All ESNs in the survey were examined, and manufacturer was identified using the first three digits of the number. All ESNs from Motorola, the manufacturer of the largest number of cellular telephones among the respondents, were reviewed by Motorola and assigned a telephone type, either handheld or other. We linked all of the data items using the cellular telephone number.

We tried to restrict the survey to individual cellular telephone users. We excluded companies based on the use of certain words or abbreviations in the name field (for example, "Company," "Inc.," "Corporation"). Companies were excluded because the account holder was not identified by name, and we had no way of knowing who had responded to the survey. We had to eliminate individuals with more than one cellular telephone from our initial sample. We found, nevertheless, that some respondents provided multiple telephone numbers or indicated more than one telephone type. We elected to include the responses from these individuals and to categorize them as "multiple telephones" in analyses that involved telephone type. We determined the degree to which the account holder accounted for the time billed (telephone "monopolization") by summing the average minutes per week of telephone use reported by the respondent for "self" and "other people" and calculating the percentage of the total reported time that the respondent attributed to personal use.

Results

A total of 3,949 users (71%) responded to the survey. In addition, we received 209 surveys from users with telephone numbers that were not included in our original sample. We presume that most of these are people with multiple cellular telephones who responded with a telephone number other than the one selected for the study. We dropped these surveys from the study because we could not link them to billing data or ESNs supplied by the telephone company.

The response rate was similar across the four geographical areas and across the three categories of level of telephone use. The median age of the respondents was 42 years (25th percentile, 34 years; 75th percentile, 51 years), and 61% of the respondents were male. We identified 431 (11%) of the telephones as business telephones and eliminated them from further analysis, leaving a total of 3,518 responses.

Telephone Type

Respondents reported the following telephone types: 26% mobile; 33% handheld; 33% transportable bag; and 8% multiple telephones. These figures did not vary appreciably within age or gender categories, but telephone type did vary considerably by geographical area (Table 1). We found telephone type, as reported by respondents with a single cellular telephone, to be highly correlated

TABLE 2. Percentage of Respondents Who Report That They Are Predominant Users of Their Cellular Telephone

		Level of Telephone Monopolization (%)	
Telephone Type	Number	≥75% of Time	100% of Time
Mobile in car	867	73	49
Handheld	1094	70	46
Bag telephone	1078	69	53
Multiple telephones	266	54	34
Overall	3,305	69	48

(r = 0.92) with telephone type as assigned by Motorola. This association was fairly constant across age and gender categories and all geographical areas.

Patterns of Use

Overall, about one-half of the respondents reported sole use of their cellular telephone, and over two-thirds reported using it at least 75% of the time (Table 2). There was only modest variation in patterns of use by telephone type, although individuals classified as having multiple telephones reported a slightly lower percentage of personal use. Percentage of telephone monopolization varied little by gender, age, or geographical area.

We examined the associations between minutes per week of use reported by respondents and the average weekly use calculated from billing data, using Spearman correlation coefficients (Table 3). The overall correlation is 0.74, with little variation by geographical area, age, or gender. We found that individuals identified as having only one cellular telephone, regardless of telephone type, reported weekly minutes of use more accurately than those with multiple telephones. When we restricted this analysis to individuals reporting 100% personal use ("sole use"), all correlations were strengthened (overall r = 0.79), and the correlation for multiple telephones (r = 0.70) was similar to that for single telephones.

TABLE 3. Spearman Correlation Coefficients of Respondents' Estimated Minutes of Use per Week and Billed Minutes per Week

	Total		Sole Users Only	
Telephone Type	Number	Correlation Coefficient	Number	Correlation Coefficient
Mobile in car	862	0.72	417	0.78
Handheld	1,116	0.74	503	0.80
Bag telephone	1,102	0.76	548	0.76
Multiple telephones	268	0.61	91	0.70
Overall	3,348	0.74	1,559	0.79

TABLE 4. Frequency Distribution (Percentage) of Tendency to Switch Sides during Telephone Use, by Telephone Type

		Frequency of Switching (%)		
Telephone Type	Number	Hardly Ever (N = 2,055)	Occasionally (N = 881)	Frequently/ Often (N = 220)
Mobile in car	887	72	23	5
Handheld	1,131	55	36	9
Bag telephone	1,138	70	24	6
Overall	3,157	65	28	7

Laterality

We show the frequency of switching the telephone from one ear to another by telephone type in Table 4. Whereas individuals with handheld telephones reported more frequent switching, fewer than 10% of all respondents reported switching the telephone frequently or often. For those with ear preferences, however, we found only a weak correlation (r = 0.15) between handedness and the preferred side (Table 5).

Discussion

Can billing records be used to assess telephone use in surveillance studies of cellular telephone users? The strong correlations that we observed indicate that billing records can serve as a reasonable measure of telephone use by the account holder. Our mailing was sent to the account holder, and we requested that this individual complete the survey. In some instances, however, others may have responded in place of the account holder. The proportion of personal use also varied by number of cellular telephones; people with multiple cellular telephones had a lower proportion of personal use. We had hoped to eliminate households with multiple cellular telephones from the survey, and therefore we did not design the survey to assess multiple telephone use. We identified multiple telephones indirectly only when the respondent took the initiative to check more than one telephone type or to record multiple cellular telephone numbers. Consequently, we likely underestimated the number of individuals in the sample with multiple telephones; some of these individuals may appear in our analysis as single telephone users. This misclassification

TABLE 5. Handedness According to Ear Preference (Portable Telephones Only)

	Ear Used by Respondent					
	Right Ear		Left Ear		Total	
Handedness	Number	%	Number	%	Number	%
Right handed	624	63	371	37	995	100
Left handed	52	39	80	61	132	100

would have led to an underestimate of the correlation between reported use and billing records, since the amount of use reported could be for a telephone other than the one selected for the survey or could represent total use of multiple telephones. Similarly, it would reduce the correlation between ESN and reported telephone type.

The high correlation that we found between ESN-derived telephone type and reported type was based on information that we received from only one manufacturer, Motorola. We have no reason to believe, however, that a respondent's reporting reliability varies by the brand of cellular telephone that he or she uses.

There appears to be a tendency for a person to favor one side of the head while holding the telephone. Only handheld portable telephones convey measurable exposure, however, and users of this type of telephone appear to have less preference to hold the telephone consistently to a particular side of the head. Furthermore, there was only a weak association between handedness and ear preference. Thus, ear preference may be an important aspect of exposure, but handedness does not appear to be a useful surrogate for identifying the preferred ear.

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Overall Mortality of Cellular Telephone Customers

Kenneth J. Rothman, Jeanne E. Loughlin, Donna P. Funch, and Nancy A. Dreyer

Unlike mobile cellular telephones, in which the antenna is not part of the handset, a portable cellular telephone exposes the user's head to radio frequency energy transmitted from the antenna. This exposure has prompted concerns about potential biological effects, including brain cancer. As a first step in a record-based mortality surveillance of cellular telephone customers, we report on overall mortality of a cohort of more than 250,000 portable and mobile telephone customers during 1994. We found age-specific rates to be similar for users of the two types of telephones. For customers with accounts at least 3 years old, the ratio of mortality rates in 1994 for portable telephone users, compared with mobile telephone users, was 0.86 (90% confidence interval = 0.47–1.53). (Epidemiology 1996;7:303–305)

Keywords: cellular telephones, mortality, electromagnetic energy, radio frequency energy.

Case reports of brain cancer among cellular telephone users have prompted investigations into the possibility that exposure to cellular radio frequency energy may have adverse health effects.[1] For cellular telephone users, the main determinant of exposure is the type of cellular telephone. Handheld portable models have the antenna in the hand piece, in close proximity to the head. In contrast, the antenna for mobile or transportable bag phones is located separately from the hand piece, and the radio frequency energy dissipates before reaching the body.[2] To evaluate the possible effect of using cellular telephones on risk of death, we have begun mortality surveillance of a cohort of telephone users. We here report preliminary findings regarding overall mortality rates of customers of a large cellular telephone carrier.

Methods

We obtained data from all cellular telephone markets covered by one of the larger U.S. cellular telephone carriers. The markets, which cover the metropolitan areas of Boston, Chicago, Dallas, and Washington DC, are served by four different data processing systems. We requested representatives of each data processing system to provide a computer file of all noncorporate, single-phone customers who had active accounts as of January 1, 1994, and who had at least two complete billing cycles with the company during November and December 1993. We excluded accounts that were clearly corporations, because it is difficult to link a corporate telephone to a specific user from the data that were available to us. We also excluded accounts that listed multiple telephones, for which we are less likely to be able to identify the actual user of each telephone. We received a total of 770,390 records from the four markets.

We requested information about each customer regarding name, address, city, state, zip code, date of birth, mobile telephone number, account number, electronic serial number (ESN) (a unique serial number embedded into each cellular telephone at the time of manufacture), Social Security number (SSN), type of telephone, and start of service date. Some of these data items were not available from the cellular carrier: date of birth, gender, and type of cellular telephone were never recorded; SSN was available for 83% of the 770,390 customers in the cohort. We contracted with a credit bureau to provide SSN, date of birth, and gender for the cohort. The credit bureau was able to find SSN for 65% of subjects, date of birth or year of birth for 63%, and gender for 78% of the records searched.

Although type of telephone (mobile *vs* portable) was not available from the billing data, we were able to assign telephone type for a large subset of customers based on the ESN. The first few characters of the ESN identify the manufacturer of the telephone. With the help of Motorola Corporation, the largest manufacturer of cellular telephones in the United States, we were able to identify the telephone type for 99% of the customers in the study who used Motorola telephones.

After receiving the raw data, we eliminated all records that had a SSN that was also listed for another record, which indicated a household with more than one telephone. This procedure reduced the file to 603,843 records with uniquely occurring SSNs. To these records, we added the data obtained from the credit bureau, and

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TABLE 1. Number of 1994 Deaths and Persons at Risk by Age, Gender, and Telephone Type

Age (Years)	Men			Women		
	Mobile	Portable	Unknown	Mobile	Portable	Unknown
20–24	0/1,023	2/1,904	2/3,069	1/1,075	0/1,263	2/2,376
25–29	2/2,985	2/3,782	7/8,406	0/2,143	1/1,923	1/5,117
30–34	1/4,879	1/5,071	8/13,801	0/2,857	0/2,238	4/6,746
35–39	3/5,723	4/5,283	15/15,293	2/3,156	0/2,384	3/7,687
40–44	1/5,540	4/4,801	16/15,011	1/3,312	0/2,480	0/7,881
45–49	8/5,442	5/4,018	28/13,773	0/3,038	0/2,091	3/6,995
50–54	9/4,135	8/2,826	21/9,850	3/2,119	6/1,497	5/4,955
55–59	13/2,770	5/1,837	21/6,661	3/1,413	2/936	4/3,237
60–64	16/2,096	8/1,317	43/4,633	5/906	1/650	8/2,124
65–69	26/1,563	17/920	55/3,210	3/708	1/450	7/1,571
70–74	30/946	10/497	44/1,932	4/454	1/255	5/1,003
75–79	9/445	6/236	28/860	3/207	1/100	7/508
80–84	7/148	5/89	18/325	1/83	0/38	0/143
≥85	3/59	2/36	3/115	0/20	0/10	0/58
Total	128/37,754	79/32,617	309/96,939	26/21,491	13/16,315	49/50,401

then we eliminated records that did not have identical SSNs and name fields from the two data sources. By limiting our selection to those customers who had identical information from two different sources, we restricted the cohort to a subset that had some validation of the information used for linkage. A total of 316,084 records remained. We eliminated an additional 75 records that had account names suggestive of a corporate account. Finally, we excluded records that lacked a year of birth or for which gender information was unconfirmed, leaving 256,284 records for linkage.

At this early stage in our surveillance, we do not yet have access to data on specific causes of death; here, we report on overall mortality during calendar year 1994. The only death file available now with data on 1994 deaths is the Social Security Administration's Death Master File, the latest release of which has deaths recorded through the first quarter of 1995. We searched this file for matches with our cohort. We considered a death record to be matched to a cohort member if the SSN matched exactly, the first five characters of the last name matched, the first letter of the first name matched, and the year of birth matched within 3 years.

Results

We found 408 deaths among cohort members that occurred before the start of 1994; we excluded these individuals from our analyses. The final cohort therefore comprised 255,868 individuals. Of these, 65% were male. The median age among the men was 42 years, and for women, 41 years. Median age was similar for users of different types of cellular telephone (mobile, 43 years; portable, 40 years; unknown telephone type, 42 years). Twenty-three per cent of the customers in the final cohort had a Motorola mobile telephone; 19% of the final cohort had a Motorola portable telephone; telephone type was unknown for the remaining 58%.

We identified 604 deaths among cohort members that occurred during 1994. In Table 1, we present the distribution of the entire cohort and those who died during 1994 by gender, age, and type of telephone used. Figure 1 gives age-specific mortality rates for portable and mobile telephone users; for this analysis, we standardized the rates among men and women to the gender distribution among portable telephone users, which is two-thirds male. The mortality curves for portable and mobile telephone users showed little difference.

We also compared mortality rates between portable telephone users and mobile telephone users who had been listed as continuing customers with the same cellular provider for at least 2 years, and, in a separate analysis, at least 3 years. For these analyses, we had fewer subjects (≥2 years of continuous use, 148,723 subjects; ≥3 years of continuous use, 63,309 subjects), but the results bear more closely on the overall effect on mortality of continuing use of portable cellular telephones. We partitioned the data into 28 strata, 14 categories of age and two of gender, and obtained the maximum likelihood estimate of the mortality rate in portable telephone users *vs* mobile telephone users.[3,4] The results of the stratified analysis are given in Table 2. They show

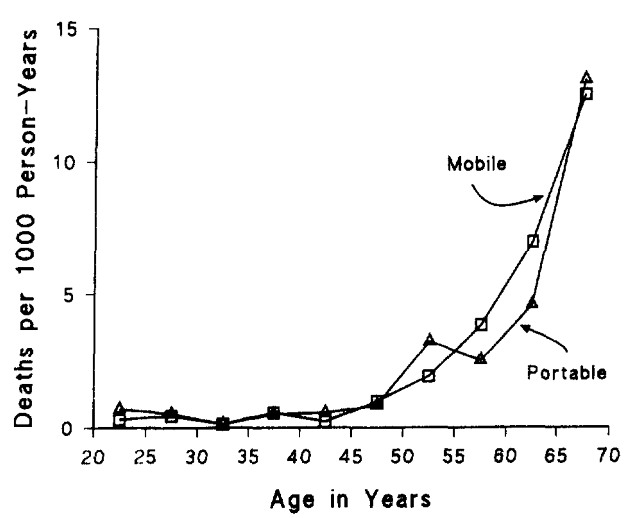

FIGURE 1. Age-specific mortality rates among users of mobile and portable cellular telephones.

TABLE 2. Mortality Rate Ratio Estimates for Portable *vs* Mobile Cellular Telephone Users of at Least 2 or 3 Years' Duration, Controlling for Age and Gender

Length of Service (Years)	Mortality Rate Ratio	90% Confidence Interval
2	0.93	0.67–1.29
3	0.86	0.47–1.53

a slightly lower rate of mortality for portable cellular telephone users. There was substantial confounding by age and gender in these analyses; the corresponding crude point estimates of the mortality rate ratio were, for those with at least 2 years of use, 0.74 rather than the unconfounded 0.93, and for 3 years of use, 0.64 rather than 0.86.

Discussion

The overall mortality rates of portable and mobile cellular telephone users are similar. The mortality rates reported here are much lower than corresponding rates for the general population, especially in the older age categories. In part, the low mortality presumably reflects the higher socioeconomic status of cellular telephone account holders. There may be additional selection factors explaining the low rates, since people who are not mobile may have little need for a cellular telephone. The Death Master File also misses some deaths and thus results in an unknown degree of underascertainment. We expect that underascertainment should be equal, however, for the users of different types of cellular telephones and therefore would not bias our comparison. Low mortality rates for cellular telephone users in general should also affect users of different types of cellular telephones nearly equally. Missing information, which led to the discarding of a substantial proportion of the original cohort, likewise should be unrelated to type of cellular telephone used.

These preliminary findings have two important limitations. First, they do not directly address the issue of the relation between cellular telephone use and brain cancer, which comprises only a small proportion of deaths. Second, the time between the exposure to radio frequency energy from portable cellular telephones and the death endpoints that we measured was comparatively short, and our study therefore addresses only short-term effects. The findings do provide evidence that there is no large short-term effect on overall mortality, and they provide a starting point for future surveillance efforts.

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